An extraordinary upwelling event in a deep thermally stratified lake

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[1] A unique combination of temporal and spatial measurements provides a description of an extraordinarily large upwelling event in Lake Tahoe, CA-NV. The 4 d event, which engulfed half of the lake's surface and had an amplitude of 500 m, was recorded with in situ and space-borne instruments. The vertical mixing that ensued, was characterized by a large transfer of heat across the thermocline, resulting in the replacement of the distinct two-layer thermal structure by a diffuse, temperature gradient. Prior to the event, mixing energy due to the cooling flux at the surface was two orders of magnitude larger than the mixing energy associated with the wind. This dominance by cooling yielded the two-layer structure. During the event, wind energy was of similar magnitude to the cooling energy. The large bottom velocities that were produced at the end of the event were sufficient to re-suspend sediment into the water column. *INDEX TERMS:* 1845 Hydrology: Limnology; 4239 Oceanography: General: Limnology; 4275 Oceanography: General: Remote sensing and electromagnetic processes (0689); 4279 Oceanography: General: Upwelling and convergences; 4546 Oceanography: Physical: Nearshore processes. **Citation:** Schladow, S. G., S. Ó. Pálmarsson, T. E. Steissberg, S. J. Hook, and F. E. Prata (2004), An extraordinary upwelling event in a deep thermally stratified lake, *Geophys. Res. Lett.*, *31*, L15504, doi:10.1029/2004GL020392.

1. Introduction

[2] Upwelling in a density stratified basin [*Mortimer*, 1952; *Monismith*, 1986; *Stevens and Imberger*, 1996] results from the surface wind stress being balanced by the horizontal pressure gradient, causing isopycnals to rise at the upwind end. Upwellings are considered partial when intermediate (metalimnetic) water reaches the surface and full (or total) when bottom (hypolimnetic) fluid surfaces [*Monismith*, 1986]. Both can have significant effects on mixing processes and thus on lake ecosystems [*Imboden et al.*, 1988], as indeed can simple seiches [*Ostrovsky et al.*, 1996].

[3] With a depth of 500 m, Lake Tahoe (39°N, 120°W) is the 11th deepest lake in the world. The long hydraulic residence time, 650 years, suggests that changes in contaminant and nutrient levels from external sources are felt slowly, whereas large-scale internal mixing processes, which can redistribute contaminants and nutrients throughout the entire lake, can impact water quality and the lake ecosystem at much shorter time scales. For example, the linkage of winter mixing to primary productivity in subsequent years and to inter-annual variability has been made, although the mechanisms of mixing were not described [*Goldman et al.*, 1989; *Jassby et al.*, 1999]. An energetic internal wave climate has been documented [*Rueda et al.*, 2003], and full upwellings that lasted for 1 d were observed over a 3-year period (Thompson, unpublished data, 1999). The present contribution describes an extraordinarily large, full upwelling event that persisted for 4 days in January, 2001, and that may have encompassed up to a half of the lake's 500 km^2 surface area, and was serendipitously observed by a range of measurements.

2. Measurements

[4] Figure 1g shows the instrument locations. Thermistor chains were deployed at Index and Midlake (labeled I and M on Figure 1g), at water depths of 124 and 464 m respectively. Each chain consisted of an array of high accuracy (0.005°C) thermistors at 2 to 40 m spacing, recording at 2 min intervals. Two acoustic Doppler velocity meters (Sontek Argonauts) were also deployed at Index, at depths of 7 m and 122 m. They measured velocity in a 1 m, vertically integrated sampling depth at 20 min averaged intervals. Water temperature, 2 cm below the surface, was collected at rafts TR1, TR2, TR3 and TR4 (labeled 1, 2, 3, 4 on Figure 1g) to an accuracy of 0.2°C. Meteorology was recorded on a pier (U on Figure 1g). Along Track Scanning Radiometer-2 (ATSR-2) satellite measurements of surface temperature for several days surrounding the described event were also acquired. The satellite measured brightness temperature, with a 1 km spatial resolution at nadir, which was corrected to surface temperature [*Hook et al.*, 2002], to an accuracy of 0.3°C. The resulting images were bi-linearly interpolated to a 500 m grid and aligned with the surveyed shoreline to improve image registration. For comparison with the in situ data, the ATSR-2 temperature nearest each surface station was extracted from the geocorrected images using nearest-neighbor sampling.

3. Results

[5] Figure 1a shows the 10 min averaged windspeed in the period surrounding the upwelling event. Winds were 2.5–3.0 m s^{-1} from the southeast, with a few 6–8 m s^{-1} events from the southwest and northeast. The higher winds led to excitation of large (30 m) amplitude, super-inertial-frequency excursions of the metalimnion, evident in both the Index and Midlake records (Figures 1d, 1e, and 1f). These oscillations correspond with the expected periods of

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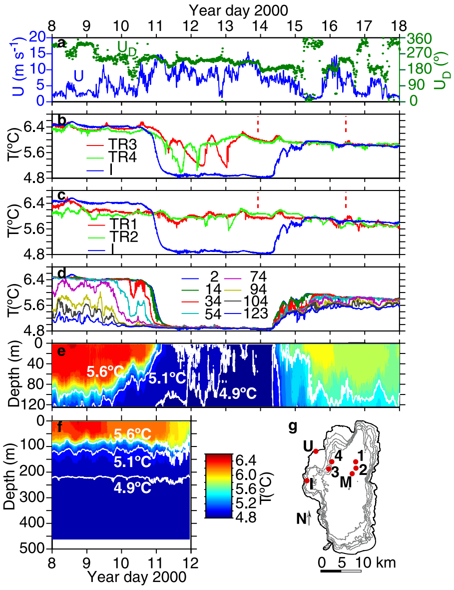

Figure 1. (a) Wind speed and direction at the USCG station, (b) Raft (TR3, TR4) thermistor time series at 2 cm depth and Index station (I) temperature at 2 m depth, (c) Raft (TR1, TR2) thermistor time series at 2 cm depth and Index station (I) temperature at 2 m depth, (d) Selected thermistor time series at the Index station (8 out of 14), (e) Filled linearly interpolated isotherms at 0.1°C intervals at the Index station, (f) Filled linearly interpolated isotherms at 0.1°C intervals at the Midlake station, (g) Depth contour (ever 100 m) map and site locations for Lake Tahoe. U is the USCG meteorological station (39°10.838′N, 120°7.157′W), I is the Index station (39°6.744′N, 120°8.932′), M is the Midlake station (39°7.535′N, 120°0.731′W) and 1–4 are the rafts TR1–TR4 respectively (39°9.180′N, 120°0.020′W; 39°9.290′N, 120°0.020 W; 39° 8.300 N, 120°4.920′W; 39°9.300′N, 120°4.330′W). The red dashed lines in frames b and c are the times of the ATSR images in Figures 4b and 4c.

Poincaré waves [*Rueda et al.*, 2003]. 9 January 2000 marked the beginning of a nearly continuous southwest wind for 5 d, followed by a 1 d southerly wind on 14 January. The middle and lower parts of the water column at Index upwelled near the end of the day on 9 January, and just before midnight on 10 January, the entire water column at Index upwelled, a condition that persisted for 4 d. This event is indicated by the period when all the thermistors sense 4.8°C to 5.0°C water. The 4.8°C was observed near the surface due to the large negative heat flux, but the rest of the water column was as cold as 4.88°C, a temperature previously observed with the bottom thermistor (463 m) at Midlake on 9 January. Isotherms at 4.9, 5.1 and 5.6°C are shown in Figures 1e and 1f for reference. The Midlake record ceases on 11 January, when the chain was deflected by the currents generated by the upwelling, and the supporting buoys deepened and collapsed.

[6] Figures 1b and 1c show surface temperatures at each raft, along with the Index record from 2 m. During the event, the surface temperature at TR3 and TR4, one third of the way across the lake, reached 5.2°C and 5.0°C, respectively. This coincides with the temperature of water that was previously measured near 100 m and between 124 and 184 m at Midlake. The locations of these rafts were

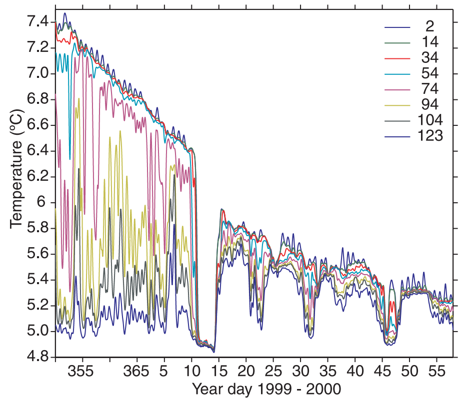

Figure 2. Selected thermistor time series for the entire deployment period at Index. A 6-hour moving average has been applied.

therefore close to the outer edge of the full upwelling. Water temperature at TR1 and TR2 decreased slightly.

[7] Figure 2 depicts the entire duration of the thermistor chain deployment, from 16 December 1999 to 26 February 2000. The near-continuous cooling rate of the surface water prior to the upwelling is evident, during which time there is a gradual increase in thickness of the surface mixed layer. The upwelling disrupts this pattern, causing rapid cooling of the surface water and warming of the deep water. The 5–7 d period waveforms superimposed on the temperature structure after the upwelling, are either sub-inertial Kelvin waves or partial upwelling events.

[8] Figure 3 shows data from the velocity meters at Index. The signal strength (Figure 3a) is related to the particulate matter present in the measuring volume. Although the absolute values of the two sensors cannot be compared, since appropriate calibrations are unavailable, the individual records are meaningful. The decrease in the signal strength at 7 m on 11 January is consistent with a decrease in particulate concentrations in the upper water column, as the water is replaced with formerly hypolimnetic water. Particle concentrations in the hypolimnion are lower than in the upper water column (J. Coker, unpublished data, 2000). The signal strength at the bottom velocity meter (122 m depth) shows little sustained deviation during the upwelling event since the sensor was always exposed to deep water. However, when the setup relaxed the entire water column at Index was

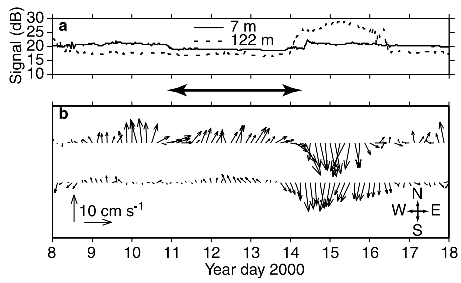

Figure 3. Argonaut velocity meter data at 7 and 122 m depths at Index, (a) Acoustic signal strength of a single beam, (b) Horizontal velocity, displayed every 3 hours. The horizontal arrow between the frames indicates the duration of the upwelling event at Index.

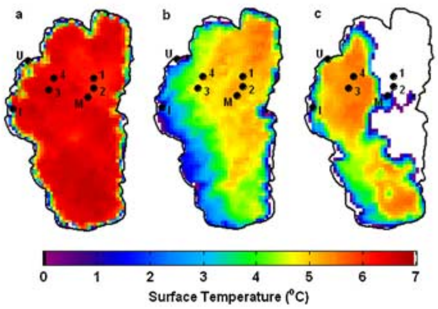

Figure 4. Satellite sensed lake surface temperature on (a) January 4 at 21:52, (b) January 13 at 22:09, (c) January 16 at 10:59. See Figure 1 for station labels.

quickly displaced southward (Figure 3b) at velocities of 10–12 cm s^{-1}, and the bottom signal strength increased dramatically. The signal strength declined just as quickly, when the velocities fell below 4 cm s^{-1}. Bottom velocities during the upwelling were only of order 1–2 cm s^{-1}, in contrast to consistent 5–7 cm s^{-1} velocities toward the northeast near the surface.

[9] The satellite imagery provides a vivid measure of the lateral extent of the upwelling. Images from before, during and after the event (Figure 4) show that up to 50% of the lake surface was affected by the event. The 4 January image shows relatively homogeneous surface temperatures across the lake, 6 d before upwelling commenced. The raft thermistor temperatures ranged from 6.2°C to 6.5°C. Calibrated ATSR-2 surface temperatures, taken from the pixels nearest each raft, ranged from 5.9°C to 6.5°C. The 14 January image, 3 d after upwelling commenced, shows significant surface cooling on the west and southwest of the lake, while the mid-lake temperatures near the rafts were still warm. The thermistor water temperature at Index at 2 m depth was 4.8°C, while the corresponding ATSR-2 surface temperature was 2.3°C. Under intense cooling conditions, as were experienced at this time (see below), temperature differences of 1–2°C could be expected between the surface and 2 m [*Schladow et al.*, 2002], which could account for most of the temperature difference at Index. Sub-visible cirrus cloud contamination likely accounts for the remaining differences between the ATSR-2 and thermistor temperatures.

[10] The image on 16 January shows significant warming on the western half of the lake as the surface temperatures return to a more homogeneous state. The thermistor surface temperature was 5.9°C at TR1, TR3, and TR4, and 5.8°C at TR2. The ATSR-2 surface temperature at TR3 and TR4 was 5.5°C. The pixels near TR1, TR2, and Index showed cloud contamination, and were not used. The colder surface water in the southwest of the lake suggests that the lake is still in a partially upwelled state. The cold pixels along the perimeter of the lake in Figure 4a are the result of shoreline contamination of the pre-subsampled pixels. This effect is less pronounced in Figures 4b and 4c due to the presence of clouds along the shoreline, which are masked in white.

4. Discussion

[11] Mixing energy was supplied to the lake in the periods before and during the upwelling event, yet the effect on the thermal stratification was markedly different during these periods. The daily average net heat flux can be calculated using bulk aerodynamic formulations and measured radiant fluxes [*Tennessee Valley Authority*, 1972]. The calculated flux incorporates measured shortwave and longwave radiation, and the computed conductive, convective and evaporative heat fluxes. This energy flux effects both the volumetric expansion and the internal energy of the lake, such that $Q_c = p\Delta v + \Delta u$, where Q_c is the net energy flux, p is the pressure (assumed constant), Δv is the change in specific mass, and Δu is the change in specific internal energy [*Rogers and Mayhew*, 1974]. The first term on the right hand side represents the change in water density that produces a potential energy gain at the surface during cooling and provides an energy source for subsequent mixing. The second term on the right hand side embodies the corresponding temperature change. The ratio of the temperature change term to the expansion term is approximately 2×10^5 [*Schladow and Fisher*, 1995]. The net heat flux must be divided by this ratio to estimate the energy flux available for mixing due to surface cooling, Q_c'.

[12] Following *Phillips* [1976], the energy flux due to momentum addition from the wind may be written as $Q_w = C_D^{\frac{3}{2}}\left(\frac{\rho_a}{\rho_w}\right)^{\frac{1}{2}} \rho_a U^3$, where C_D is a drag coefficient (1×10^{-3}), ρ_a and ρ_w are the densities of air and water respectively, and U is the windspeed.

[13] The energy inputs for mixing from cooling and from direct wind effects are shown in Figure 5. They act additively to produce mixing, so the mixing from cooling is defined positive as heat loss from the lake. It can be seen that the energy available for mixing is dominated by cooling processes, and that wind acting through momentum input approaches such a sustained level of energy only during the period of full upwelling. Generally the cooling energy is 1 to 2 orders of magnitude greater than the direct wind energy.

[14] Figure 2 also indicates that the mixing of the water column prior to and during the upwelling event produced markedly different effects on the water column. In the period up to the large upwelling event, deepening of the surface layer occurred at the expense of the metalimnion. The structure of the metalimnion, however, was generally preserved. Upwelling resulted in the elimination of the surface mixed layer as such, and the mixing of the water column (Figure 6). Prior to the event, top to bottom temperature differences at the Index station were nearly 1.5°C. After the event the temperature difference was 0.3°C,

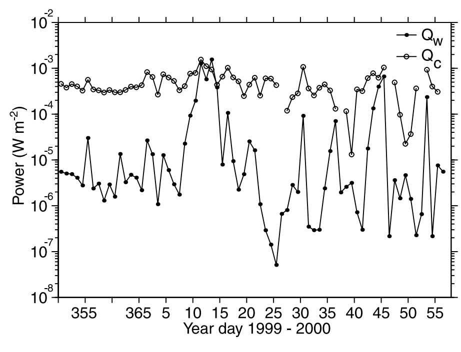

Figure 5. Available mixing energy from surface cooling, Q_c', and from wind, Q_w, for the entire record.

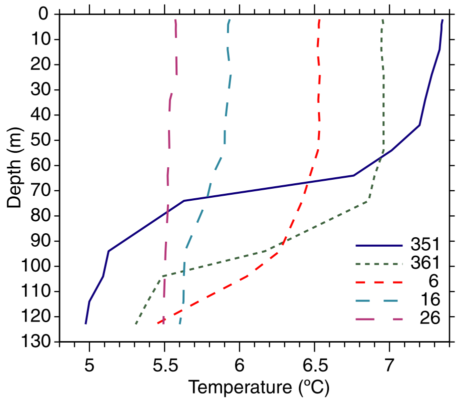

Figure 6. Temperature profiles from the thermistor chain at Index Station, at 10-day intervals. All profiles were collected near 00:00 hours on the day indicated.

with both the surface and bottom water temperatures having changed by 0.6°C (Figures 1c, 2, and 6). Rather than resulting in net deepening of the surface layer, the event led to large dispersion of heat across the metalimnion. This would be consistent with convective mixing of the cold, upwelled water with the underlying water as it is drive across the lake's surface.

[15] The drop in signal strength at the upper velocity instrument is consistent with clearer bottom water being advected upward. This is also confirmed by a vertical plankton tow performed mid-morning on January 14, which showed that the upper water column was essentially free of plankton. The Secchi depth measured at noon that day was 33 m, a dramatic increase from the reading on December 31 of 19.75 m (R. C. Richards, unpublished data, 2000). When the setup relaxed, the signal strength, the plankton population and the Secchi depth returned to pre-upwelling levels. The signal strength increase in the bottom velocity instrument is attributed to a resuspension of bottom sediments. The elevated signal lasted more than two days, coinciding with a near-bottom flow in excess of 10 cm s^{-1}.

5. Conclusions

[16] The upwelling event described is extremely large, both in terms of the amplitude of water excursions (500 m) and the overall duration (4 d). The event brought dense bottom water into the surface drift, traveling at approximately 5–7 cm s^{-1} to the north-northeast (Figure 3b), which would inevitably lead to instability and thus mixing. The character of this mixing was very different than the "normal" pattern of dominance by natural convection characterized by deepening and sharpening of the thermocline. Instead a more diffuse temperature structure was produced in the upper water column, accompanied by a major exchange of heat across the thermocline.

[17] Likely effects of the event include dislocation of nutrients and plankton, and change in light climate. The bottom water that is brought up to the surface during a full upwelling transports nutrients upward from the hypolimnion, an event that usually only occurs during deep springtime vertical mixing in Lake Tahoe [*Paerl et al.*, 1975]. The resuspension of bottom material was also a significant feature, which in turn has the potential to exacerbate horizontal and vertical transport of nutrients and contaminants. Given that full vertical mixing of Tahoe occurs only every few years, this upwelling and other partial upwellings may represent an important mechanism for driving ecosystem functions.

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